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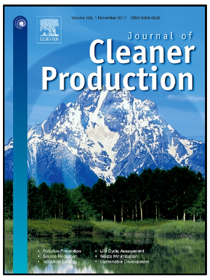

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Optimization of freeze-drying using a Life Cycle Assessment approach: strawberries' case study

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ABSTRACT

Drying of foods is a preservation method that aims to prolong the product shelf life and simplify its transport and storage. However, this process requires a large amount of energy, which results in high emissions of contaminants in the environment.

In this work, Life Cycle Assessment (LCA) analysis was applied to the drying of strawberries. In particular, for the first time, traditional freeze drying and the combination of osmotic dehydration + freeze drying were analysed and compared to verify if the application of the pre-treatment was effective in reducing the environmental impact, obtaining a more sustainable process.

The chosen functional unit was one 450 g dried strawberries' package. Strawberries were gathered in 2016, from May to September. Primary data related to the drying process were used to perform mass and energy balances and compile the life cycle inventory. The LCA analysis was accomplished using SimaPro 8.0.5 software, in accordance with ISO 14040-14044. The calculations on the traditional freeze drying process were made considering actual operation factory data, whereas the calculations on the osmotic + freeze drying process were desk calculations. The comparison of freeze drying and osmotic dehydration + freeze drying on industrial scale revealed that the traditional process generated higher emissions in terms of all the studied environmental categories. A scenario analysis was, then, carried out to evaluate the potential emissions' reduction due to the variation of some process times.

An improved scenario based on the use of osmotic dehydration + freeze drying with optimised process times was, therefore, proposed; using the improved process, a reduction of the emissions equal to 25 % with respect to the traditional freeze drying process could be obtained.

Sensitivity analysis showed that variations in fertilisers' amount and in condenser and vacuum pump power did not cause significant changes to the results. The results also showed moderate sensitivity to strawberries' transport distance.

KEYWORDS: LCA; Emissions; Food drying; Freeze drying; Osmotic dehydration.

1. INTRODUCTION

Drying of foods is a common preservation process, which allows inhibiting microbial spoilage and enzyme activity and, therefore, extends the product shelf life (de Bruijn et al., 2016). Moreover, the decrease in product weight simplifies transport and storage (Brown et al., 2008). Two main parameters are commonly employed to evaluate the degree of drying: moisture content (MC), which is the quantity of free and bond water contained in the food, and water activity (a_w), which provides an indication of food stability with respect to microbial growth. It has been extensively observed that, in order to avoid bacterial proliferation, MC should be lower than 20-25 % (de Bruijn et al., 2016) and a_w lower than 0.6 (Stevenson et al., 2015).

Among the available drying techniques, freeze drying represents the most effective method since it allows high water removal, while preserving most of the fresh food characteristics. This process is based on the freezing of the product, followed by sublimation of the ice at reduced pressure. In order to achieve the required MC and a_w, however, long processing times and a considerable quantity of energy are needed.

Drying time can be reduced, and, therefore, energy consumption decreased, applying some pre-treatments prior to freeze drying (Sagar and Kumar, 2010). The reduction of energy consumption would generate not only economic advantages but also the attainment of more sustainable productions. Among pre-treatments, osmotic dehydration has become popular, due to its low cost and complexity (Kaushal and Sharma, 2016). It consists of the immersion of the product in a heated hypertonic solution and, due to the semi-permeability of the cell membrane, water is removed more quickly than sugar is taken by the cells (Floury et al., 2008). The application of this pre-treatment allows an intermediate moisture product to be obtained, which can then be completely dried in a reduced period of time in a freeze dryer (Prosapio and Norton, 2017).

Food preservation requires a large amount of energy, resulting in high emissions of contaminants in the environment, especially CO_2, which is the major responsible for the greenhouse effect (Manfredi and Vignali, 2015). For this reason, it is crucial to assess and quantify the related energy consumption to identify the most energy consuming steps and understand where it is possible to intervene to minimise the emissions.

The environmental impact of a product or a process throughout its life cycle was frequently estimated using Life Cycle Assessment (LCA), an ISO certified methodology, which allowed the quantification of all the resources consumed and of all the emissions and wastes released.

In the last few years, the application of LCA evaluations in food and beverages industries has increased considerably, because their unit operations are energy intensive (Roy et al., 2009). In this field, papers have been focused on the environmental impact of packaging systems in the case of coffee (De Monte et al., 2005), beverages (Manfredi and Vignali, 2015), food in general (Pardo and Zufía, 2012) or in the case of treatments for the conservation of foods, such as jams and marmalades (De Marco and Iannone, 2017).

Some industrial processes have been studied, such as the production of Italian red and white wines (Iannone et al., 2016), Spanish aged red wines (Meneses et al., 2016), beer (De Marco et al., 2016), tomato ketchup (Andersson et al., 1998), tomato puree (Manfredi and Vignali, 2014), Swedish cheese (Berlin, 2002), milk (de Boer, 2003), dairy products (Berlin et al., 2007), meat (Biswas and Naude, 2016) and treatments of food waste (Cristóbal et al., 2016).

Drying employs approximately 20-25 % of the total energy consumed by food industry (Kumar et al., 2014). Among the drying processes, some environmental studies have been performed on coffee drying (Humbert et al., 2009), on laboratory and industrial spray drying (Ciesielski and Zbicinski, 2010) or on the comparison of drum drying and spray drying (De Marco et al., 2015), but no LCA study has been carried out on freeze drying so far.

In order to fill this gap, in this work, a comparative LCA analysis according to a cradle-to-grave approach (considering agricultural stages, process stages, packaging and end of life of materials) will be performed on freeze drying and osmotic dehydration + freeze drying of strawberries. The environmental impact of the two techniques will be evaluated and the phases most affecting the emissions related to the entire process will be identified. The impacts related to 450 g freeze dried strawberries and 450 g osmotic + freeze dried strawberries' package will be compared and discussed.

In literature, the majority of papers based on LCA studies looked at the process as a "black box", without evaluating the emissions related to the single unit operations that constitute the whole process. In this paper, the analysis will be carried out taking into account the contributions of each process phase (Sanjuán et al., 2014), using primary United Kingdom industrial data, with the aim of modifying the traditional process of frozen strawberries' production. Indeed, the industrial world is interested in the modification of traditional processes with the aim of obtaining more sustainable productions with, as far as possible, limited emissions.

2. PROCESS DESCRIPTION

2.1 *Prime operations*

Fresh strawberries (*Malling centenary*) were cultivated in Norfolk, in the east cost of UK and, after harvesting and transportation by truck, were stored in a refrigerator at 5 °C. After a destemming, they were freeze dried in the traditional process or they are osmotic dehydrated and, then, freeze dried.

2.2 Osmotic pre-treatment

Osmotic pre-treatment was carried out by immersion of strawberry cubes in an osmotic solution formed by fructose and water, at 50 °C, under stirring at 250 rpm, for 3 hours. Strawberries had a starting water content equal to 86.4 %, whereas after the osmotic pre-treatment their water content was equal to 18.8 %. The fruit to solution ratio (F:OS) was fixed at 1:10 and the concentration of the osmotic solution was fixed at 60 °Bx (60 g of fructose and 40 g of water). After the osmotic dehydration, strawberries were taken, blotted with paper and frozen for 18 hours at -20 °C.

2.3 Freeze drying

In freeze drying process, destemmed strawberries were cut into 1 cm^3 pieces in volume to increase the surface area, frozen at -20 °C and then lyophilised using a condenser temperature equal to -110 °C, and a pressure equal to 10 Pa (Prosapio and Norton, 2017). The working pressure is lowered by a rotary pump below the triple point of water, equal to 607 Pa, to allow the ice sublimation. In order to achieve the same final values in terms of MC (7.4 kg/100 kg) and a_w (0.195), the processing time was fixed equal to 18 hours in classic freeze drying and equal to 7 hours when freeze drying was applied downstream osmotic dehydration.

2.4 Packaging and waste disposal

According to a recent trend aimed at decreasing the emissions due to food industrial productions (Ruggieri et al., 2009), the organic wastes (stems, defected strawberries) were composted. For the end of life of packaging materials, the English scenario was considered and data on recycling, incineration and landfill percentages provided by UK specific consortia were taken into account. In particular, for plastic materials, the 16 % was recycled, the 54 % was used for energy recovery and the 34 % was landfilled (RECOUP, 2016); for paper, the 73.1% was recycled and the 26.9 % was landfilled (GOV.UK, 2014).

2.5 Moisture content and water activity analyses

Moisture content (MC) analyses were carried out using a moisture analyser. A halogen element guarantees a uniform infrared heating at a temperature of 120 °C until the sample weight becomes constant. The weight change allows the calculation of moisture percentage. Strawberry initial moisture content was found to be equal to 0.86 kg/1 kg, whereas strawberry final moisture content was equal to 0.074 kg/1 kg.

Water activity (a_w) of fresh and dried samples was measured using a dew point water activity meter. The temperature controlled sample chamber was set to 25 °C. The water activity of the fresh samples was equal to 0.988; water activity of dried strawberries was equal to 0.195; the value is well below the limit of 0.6 reported in literature for the bacterial proliferation (Stevenson et al., 2015).

3. LCA METHODOLOGY

The first step towards achieving cleaner food productions is the determination of the environmental impact of the product. It can be done through a life-cycle assessment (LCA) analysis, which is a quantitative method to evaluate the emissions to soil, water and air. Therefore, this analysis is useful to compare different processes, or to identify the most critical stages of a specific production, from the environmental point of view. In the LCA methodology, it is important to focus some points: 1) define the scope of the LCA analysis, choosing the functional unit and delimiting the system boundaries; 2) collect data, perform heat and mass balances and compile the life cycle inventory (LCI); 3) determine emissions to water, air and soil through a proper LCA method.

3.1 Scope of the LCA analysis, functional unit and system boundaries

The first step it to define the goal of the LCA analysis; this step is crucial because the entire study will be influenced by the assumptions made at this stage. The scope of this LCA study is a comparative evaluation of the impacts caused by dried strawberries' production and packaging. Strawberries were treated using two different techniques and packaged. In particular, in the first process, strawberries were frozen at -20 °C, lyophilised and packaged, whereas, in the second one, they were osmotically pre-treated, frozen, lyophilised and packaged.

Inputs (raw materials, water and energy) and outputs (products, water and emissions) have to be related to the functional unit (FU), which can be the weight of the product under analysis. The functional unit of this study was 450 g of strawberries produced by freeze drying and osmotic dehydration + freeze drying processes.

For cradle-to-grave quantification, mass and energy balances related to each step of the process were performed. The system boundaries (identified by the dashed line in Figure 1) were set from strawberries' plantation to dried strawberries' packaging. Figure 1a refers to the classic lyophilisation process, whereas Figure 1b to the osmotic dehydration + lyophilisation. The distribution of the products was not considered and, therefore, not included in the system boundaries, whereas the management of wastewater, organic wastes and packaging materials was taken into account. In Table 1, the main details of the two processes are listed.

Table 1. Process details and assumptions

Process	Characteristics and details
Agricultural stages	Energy and water supply Insecticide, pesticide and herbicide supply Nitrogen and fertilizer supply
Strawberries supply to facility	Transport by truck, 16 ton from Norwich, England; distance = 250 km
Energy supply to facility	England energy mix medium voltage

Freezing	T= -20 °C; t = 18 h; energy supply
Vacuum drying	T = -110 °C; t = 18 h; P = 10 Pa; energy supply
Packaging	Energy, supporting materials and components supply
Osmotic pre-treatment	T = 50 °C; t = 3 h; energy and water supply
Freezing	T= -20 °C; t = 18 h; energy supply
Vacuum drying	T = -110 °C; t = 7 h; P = 10 Pa; energy supply
Packaging	Energy, supporting materials and components supply

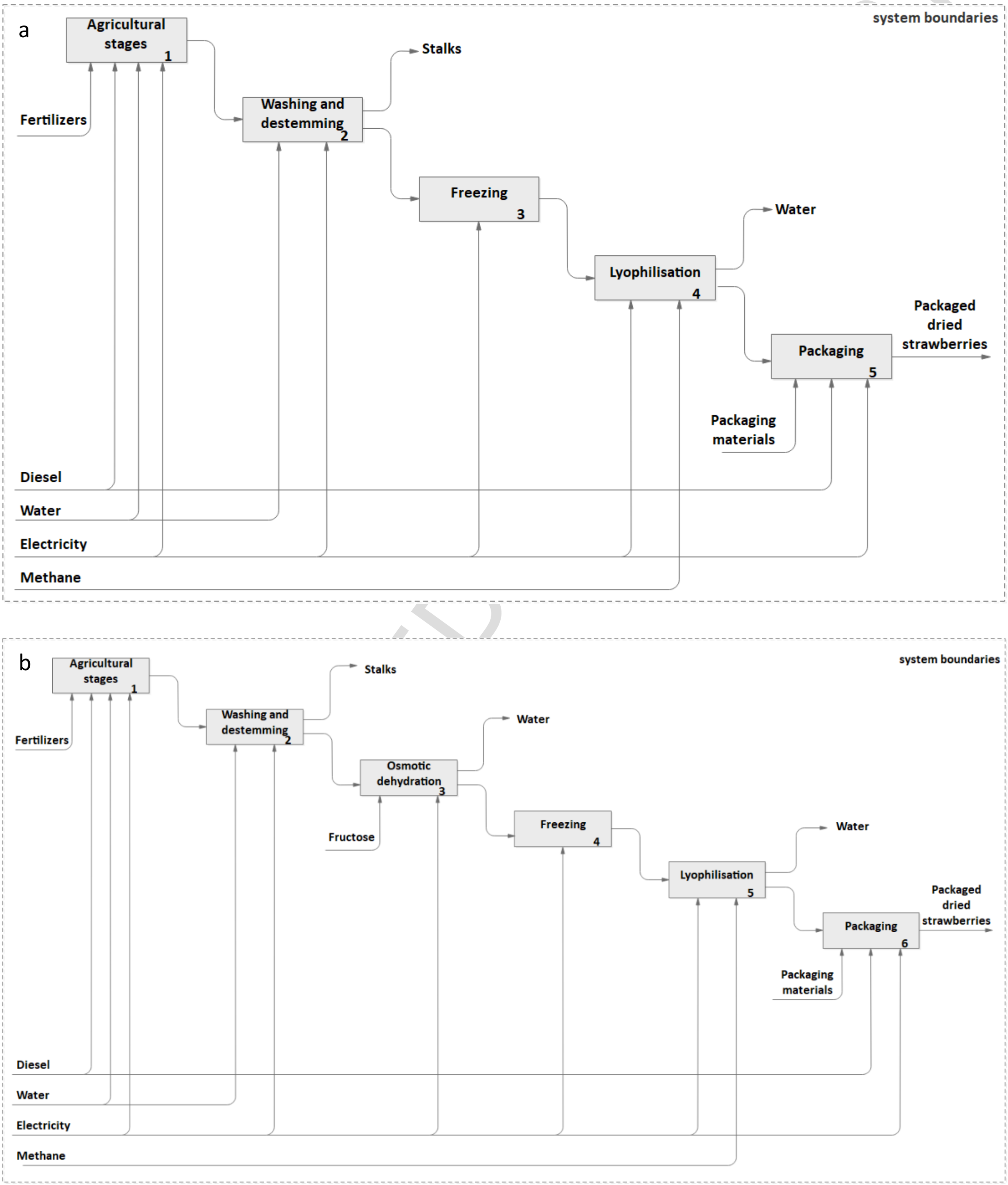


Figure 1. IDEF diagrams of dried strawberries production; a) freeze drying scheme; b) osmotic pre-treatment + freeze drying scheme.

3.2 Data collection and compiling of the inventory

Once defined the goal of the analysis, it is necessary to search and collect process data, in order to compile the life cycle inventory (LCI). This is one of the most time- and effort-consuming step because data necessary for the environmental assessment of the observed system need to be, first, collected and, then, linked through mass and heat balances. In the present study, data regarding amount of materials, water, electricity and fuels used during each step of the process were collected directly from the drying plants. Background inventory data related to the production of 1 kWh of electricity were compiled by considering the United Kingdom production mix from Treyer and Bauer (Treyer and Bauer, 2016); inventory data regarding water were recovered from Pfister el al. in the case of agricultural stages (Pfister et al., 2011) and from Althaus et al. in the case of processing stages (Althaus et al., 2007). Since ISO 14040-14044 (the reference standard for LCA) recommends avoiding allocation, single processes producing single outputs were considered in the present study. The LCA study was performed using the LCA software SimaPro 8.0.5 (PRé Consultants, 2015) in agreement with ISO 14040-14044, that are the reference standard for LCA. For each process unit, input data (such as natural sources, water and energy) and output data (emissions to air, water and soil) were collected and linked together. The numerical results obtained after heat and mass balances, regarding the main inputs and outputs are listed in Table 2.

Table 2. Life cycle inventory of the main inputs and outputs for dried strawberries' production; data are referred to the production of 450 g of packaged strawberries.

Industrial Phase	Input/Output	Unit	Freeze drying	Osmotic + freeze drying
Agricultural	Pesticide	kg	2.27E-03	2.27E-03
	Fungicide	kg	4.68E-04	4.68E-04

	Calcium nitrate	kg	6.02E-02	6.02E-02
	Potassium nitrate	kg	8.80E-02	8.80E-02
	Monoammonium phosphate	kg	1.66E-02	1.66E-02
	Magnesium sulfate	kg	8.38E-03	8.38E-03
	Irrigation	kg	3.14E+00	3.14E+00
Transportation	Cultivated strawberries	kg	3.14E+00	3.14E+00
	Transport by truck	tkm	7.70E-01	7.70E-01
Destemming	Strawberries	kg	3.11E+00	3.11E+00
	Output			
	Waste	kg	2.59E-01	2.59E-01
Osmotic treatment	Destemmed strawberries	kg	2.85E+00	2.85E+00
	Water	kg		1.14E+01
	Fructose	kg		1.71E+01
	Electricity	MJ		2.67E-01
	Output			
	Wastewater	kg		1.38E+01
Freezing	Strawberries	kg	2.85E+00	4.77E-01
	Electricity	MJ	1.18E+00	1.98E-01
Vacuum drying	Frozen strawberries	kg	2.85E+00	4.77E-01
	Electricity	MJ	2.10E+00	4.36E-01
	Output			
	Water	kg	2.43E+00	5.87E-02
Packaging	Strawberries	kg	4.50E-01	4.50E-01
	Polyethylene	kg	1.00E-02	1.00E-02
	Cardboard	kg	3.86E-04	3.86E-04
	Electricity	MJ	1.28E-02	1.28E-02
	Output			
	Packed strawberries	p	1	1
Waste disposal	Polyethylene	kg	1.00E-02	1.00E-02
	Cardboard	kg	3.86E-04	3.86E-04

3.3 Method for impact assessment

Among the LCA methods integrated into SimaPro 8.0.5 software, the ReCiPe method was chosen, since it is one of the most recent and complete (Goedkoop et al., 2009). This method quantified the emissions due to a process both in terms of eighteen characterization factors (midpoint level) and in terms of damage factors (endpoint level). The midpoint categories and their abbreviations are listed in the first two columns of Table 3. These midpoint categories can be aggregated into three endpoint categories, in order to evaluate the damages to human health (HH), to ecosystem diversity (ED) and to resource availability (RA). The ReCiPe method handles uncertainty considering three time perspectives or scenarios: individualist (I) is based on the high capacity of adaptation of humans and, therefore, consider a short-time horizon; egalitarian (E) is the most precautionary perspective, taking into account long time horizons; hierarchist (H) is in the middle and is based on the most common policy principles with regards to time-frame. In this work, the hierarchist perspective, which is the most balanced one, was chosen.

4. RESULTS AND DISCUSSION

4.1 Environmental dried strawberries' production analysis at midpoint level

The aim of this study was the evaluation and comparison from the environmental point of view of freeze drying techniques. Since dried strawberries obtained using the two techniques showed comparable properties in terms of moisture content, water activity and textural properties (Prosapio and Norton, 2017), this study claimed to understand which was the most eco-friendly process. Therefore, a comparative LCA analysis was performed using the midpoint categories included in the ReCiPe method, considering all the phases of the two productions, from agricultural stages to end-of-life. The quantitative values of the emissions at midpoint level for the two productions under analysis are reported in Table 3, while a comparison between the processes is graphically reported in Figure 2.

Table 3: ReCiPe midpoint results for strawberries production. Data are referred to the functional unit (450 g).

Midpoint category	Abbreviation	Unit	Freeze drying	Osmotic + Freeze drying
Climate change	CC	kg CO_2 eq	1.28E+00	9.46E-01
Ozone depletion	OD	kg CFC-11 eq[1]	2.31E-07	2.07E-07
Terrestrial acidification	TA	kg SO_2 eq	6.65E-03	5.08E-03
Freshwater eutrophication	FE	kg P eq	2.77E-04	1.63E-04
Marine eutrophication	ME	kg N eq	1.49E-02	8.10E-03
Human toxicity	HT	kg 1,4DCB eq[1]	2.60E-01	1.75E-01
Photochemical oxidant formation	POF	kg NMVOC[1]	4.70E-03	4.06E-03
Particulate matter formation	PMF	kg PM_{10} eq	2.04E-03	1.59E-03
Terrestrial ecotoxicity	TET	kg 1,4DCB eq[1]	4.04E-03	4.01E-03
Freshwater ecotoxicity	FET	kg 1,4DCB eq[1]	9.44E-03	5.71E-03
Marine ecotoxicity	MET	kg 1,4DCB eq[1]	8.91E-03	5.33E-03
Ionizing radiation	IR	kBq U235 eq[1]	2.31E-01	1.03E-01
Agricultural land occupation	ALO	m^2 x yr	1.30E+00	1.29E+00
Urban land occupation	ULO	m^2 x yr	7.25E-03	4.52E-03
Natural land transformation	NLT	m^2	1.87E-04	9.00E-05
Water depletion	WD	m^3	1.79E-02	1.70E-02

Mineral resource depletion	MRD	kg Fe eq	3.97E-02	3.35E-02
Fossil fuel depletion	FD	kg oil eq	3.52E-01	2.32E-01

[1] CFC-11: Chlorofluorocarbon; 1,4DCB: 1,4 dichlorobenzene; NMVOC: Non Methane Volatile Organic Carbon compound; U235: Uranium 235.

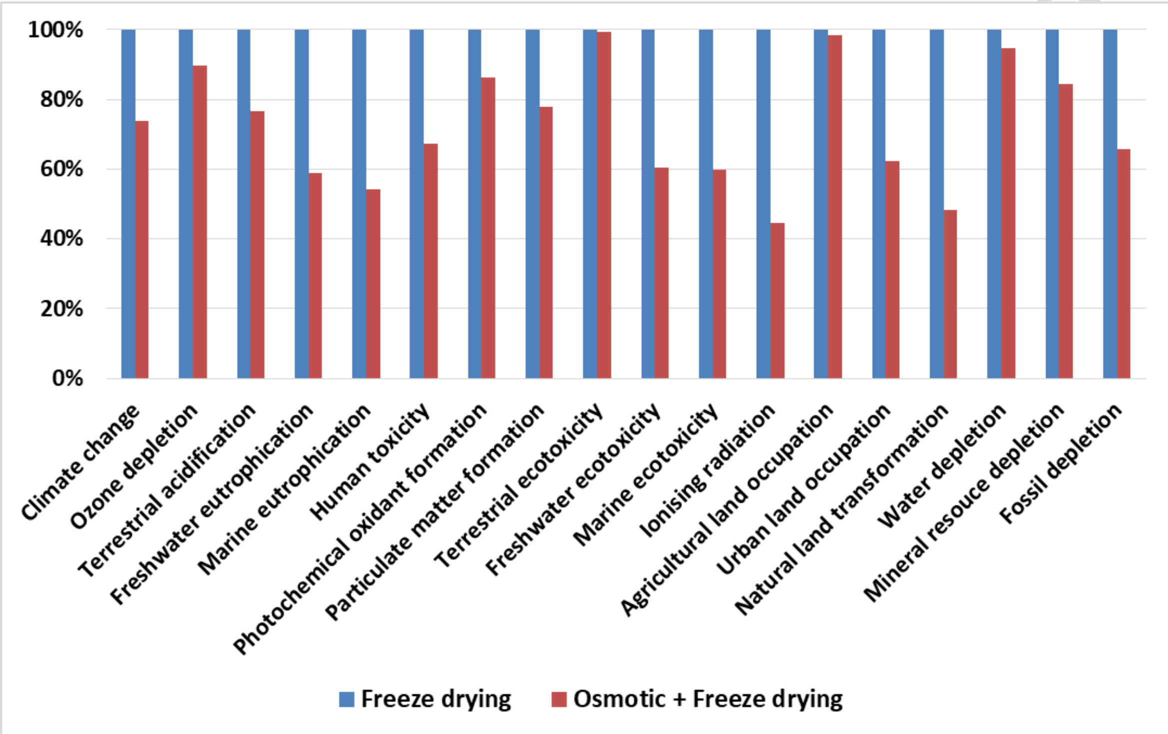


Figure 2. Comparison of the impacts of the two strawberries' productions per FU.

It is evident that the process based on traditional freeze drying generated higher emissions in terms of all the midpoint categories. The higher differences in the emissions are noticeable for freshwater ecotoxicity, marine ecotoxicity and ionising radiation; this is due to the longer process time and, therefore, mainly to the higher quantity of electricity used during the vacuum drying process, in the case of the traditional process. In order to better visualise this difference, the relative contributions of the different stages (agricultural, transportation, processing, and packaging) of the two productions are reported in Figure 3a and 3b. The end of life was considered in the stage of packaging.

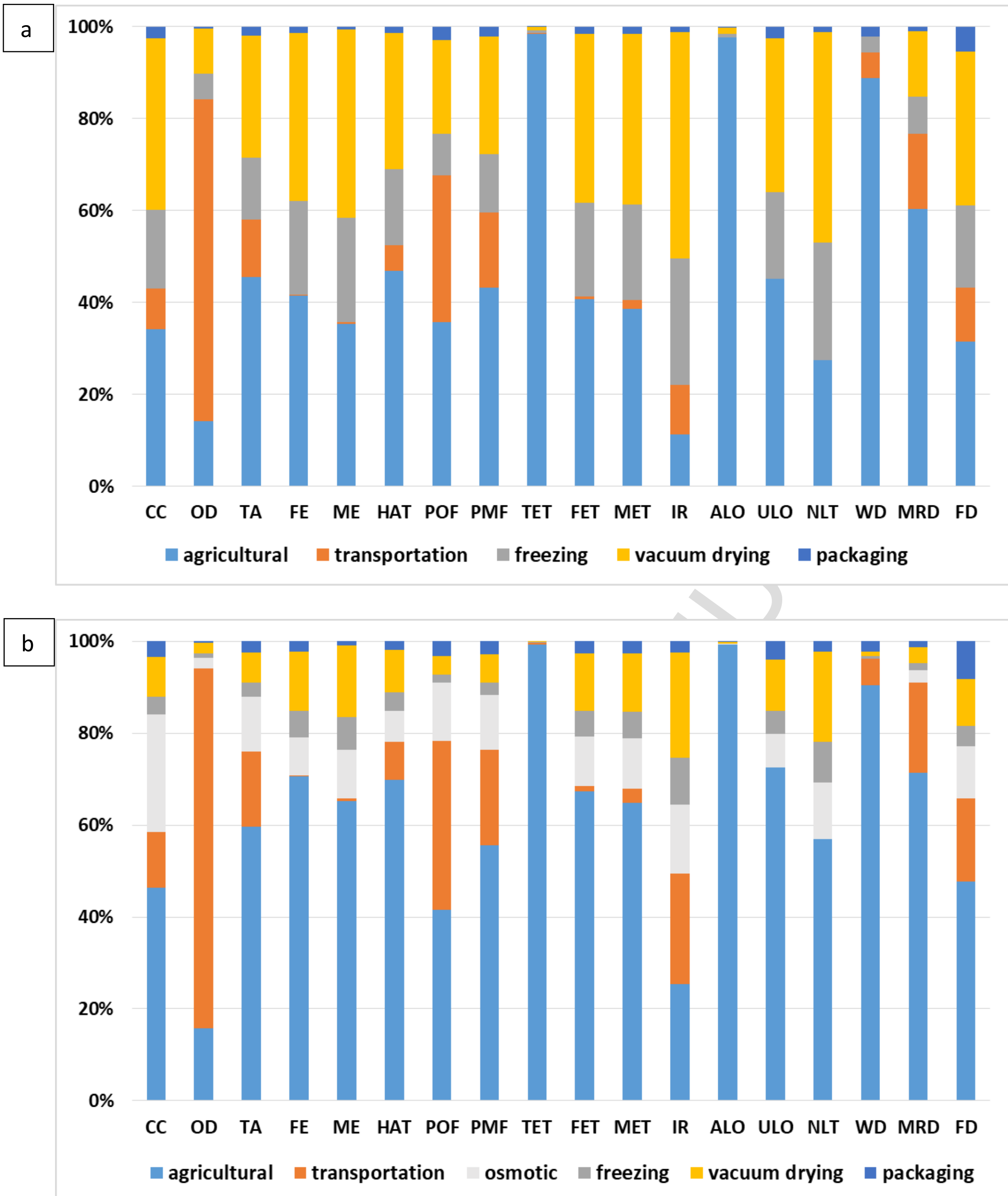


Figure 3. Relative contributions of the phases with respect to the overall impacts for the two productions: (a) freeze drying; (b) osmotic dehydration + freeze drying.

It is possible to observe that, in the case of freeze drying, the relative contributions of the agricultural and transportation steps were higher than the contribution of processing steps in terms of ozone depletion, terrestrial acidification, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, agricultural land occupation, water depletion and mineral resource depletion, whereas the processing steps' contribution is higher in terms of the other midpoint categories.

In the case of osmotic dehydration + freeze drying technique, the relative contributions of the agricultural and transportation steps were higher than the contribution of processing steps in terms of the majority of the midpoint categories; they were comparable in terms of ionizing radiation, whereas the contribution of processing phases was higher in terms of freshwater ecotoxicity and marine ecotoxicity.

For both the productions, the contributions of the packaging phase (containing also the end of life of packaging materials) were negligible in comparison with the other contributions.

In Table 4, the ReCiPe midpoint results for the processing phases were evaluated and reported. In order to perform a comparative analysis, the agricultural, transportation and packaging stages, which were common to the two processes were not taken into account.

Table 4: ReCiPe midpoint results for processing phases of dried strawberries' production. Data are referred to the FU (450 g).

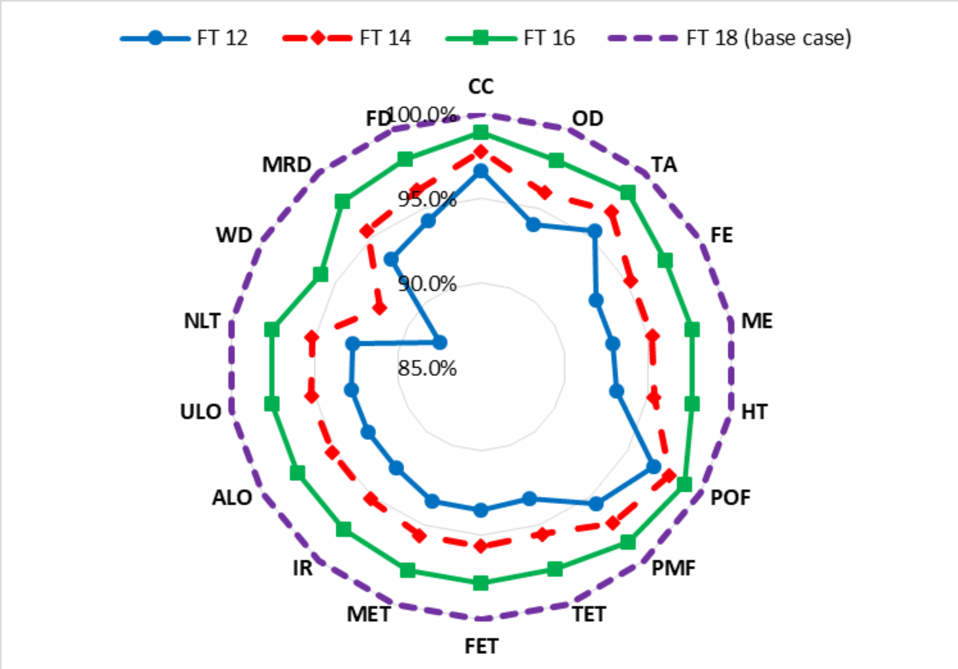
Midpoint category	Unit	Freeze drying		Osmotic + freeze drying		
		Freezing	Vacuum drying	Osmotic	Freezing	Vacuum drying
CC	kg CO_2 eq	2.18E-01	4.78E-01	2.42E-01	3.65E-02	8.28E-02
OD	kg CFC-11 eq[1]	1.25E-08	2.28E-08	4.79E-09	2.10E-09	4.64E-09
TA	kg SO_2 eq	8.89E-04	1.77E-03	6.12E-04	1.49E-04	3.33E-04
FE	kg P eq	5.67E-05	1.01E-04	1.36E-05	9.50E-06	2.10E-05
ME	kg N eq	3.40E-03	6.11E-03	8.55E-04	5.70E-04	1.26E-03
HT	kg 1,4DCB eq[1]	4.30E-02	7.71E-02	1.17E-02	7.20E-03	1.59E-02
POF	kg NMVOC[1]	4.32E-04	9.60E-04	5.13E-04	7.23E-05	1.64E-04
PMF	kg PM_{10} eq	2.60E-04	5.22E-04	1.90E-04	4.35E-05	9.75E-05
TET	kg 1,4DCB eq[1]	1.77E-05	3.21E-05	5.27E-06	2.97E-06	6.56E-06
FET	kg 1,4DCB eq[1]	1.93E-03	3.46E-03	6.13E-04	3.22E-04	7.12E-04
MET	kg 1,4DCB eq[1]	1.85E-03	3.32E-03	5.83E-04	3.09E-04	6.83E-04
IR	kBq U235 eq[1]	6.37E-02	1.14E-01	1.54E-02	1.07E-02	2.35E-02
ALO	m^2 x yr	9.76E-03	1.74E-02	2.28E-03	1.63E-03	3.61E-03
ULO	m^2 x yr	1.36E-03	2.43E-03	3.29E-04	2.28E-04	5.03E-04
NLT	m^2	4.79E-05	8.54E-05	1.15E-05	8.02E-06	1.77E-05
WD	m^3	6.60E-04	0.00E+00	0.00E+00	1.10E-04	1.93E-04
MRD	kg Fe eq	3.16E-03	5.65E-03	9.35E-04	5.29E-04	1.17E-03
FD	kg oil eq	6.31E-02	1.18E-01	2.64E-02	1.06E-02	2.35E-02

[1] CFC-11: Chlorofluorocarbon; 1,4DCB: 1,4 dichlorobenzene; NMVOC: Non Methane Volatile Organic Carbon compound; U235: Uranium 235.

4.2 Scenario analysis and improved solutions

Once assessed that the less impactful process is the osmotic dehydration + freeze drying, new experiments were performed on a bench scale plant using this process, with the purpose of identifying the operating conditions that allow the lowering of the emissions, ensuring the quality of the product. Therefore, the effect of the freezing time and of the vacuum drying time on the strawberries' moisture content (MC) and water activity (a_w) was evaluated. Experiments varying the freezing time in the range 6 – 18 hours and the vacuum drying time in the range 3 – 7 hours were performed. It was noticed that, in order to avoid microbial spoilage in the dried strawberries, the minimum freezing time to be employed was equal to 12 hours and the minimum vacuum drying time was equal to 4 hours.

Therefore, a scenario analysis was performed (Beccali et al., 2010) on the industrial scale plant to estimate the influence of the modification of the two process times on the midpoint categories. The base case was the one previously analysed, in which a freezing time of 18 hours and a vacuum drying time of 7 hours were considered. For each improved scenario, four different levels of times were chosen for both the variables under study. In particular, the chosen freezing time (FT) levels were: (a) 12 hours; (b) 14 hours; (c) 16 hours; (d) 18 hours (base case); whereas the chosen vacuum time (VT) levels were: (1) 4 hours; (2) 5 hours; (3) 6 hours; (4) 7 hours (base case). The effect of the lowering of the two process times at ReCiPe midpoint level was reported in the two radar charts in Figure 4.



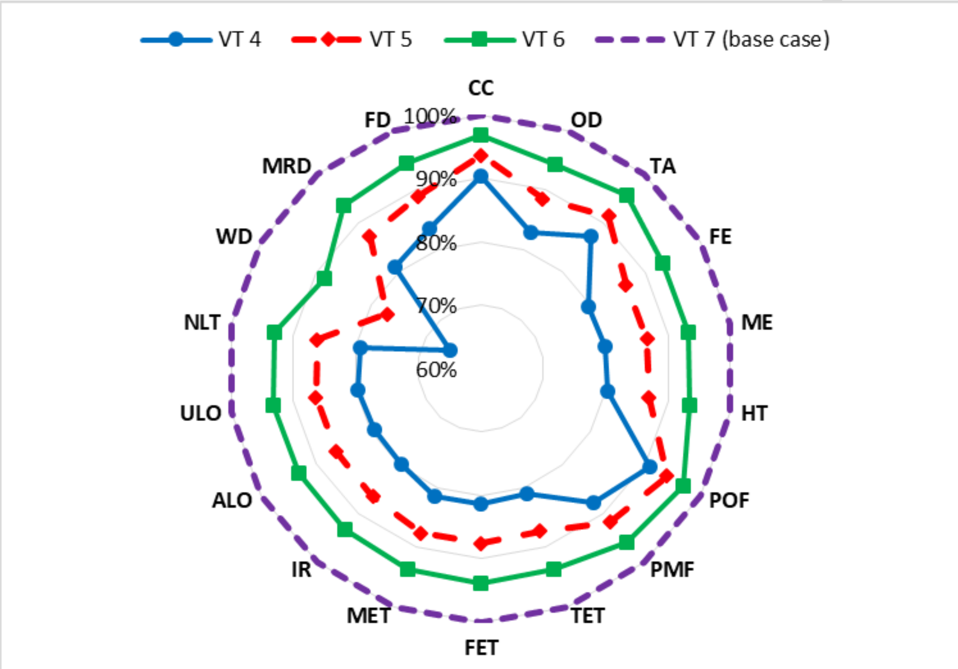


Figure 4. Scenario analysis: (a) freezing times (FT) equal to 12, 14, 16 and 18 hours; (b) vacuum times (VT) equal to 4, 5, 6 and 7 hours.

It is possible to observe that the reduction of the vacuum time generates an appreciable decrease in the emissions at midpoint level, whereas a moderate reduction can be observed decreasing the freezing time. Indeed, a freezing time equal to 12 hours generated an average reduction of the emissions equal to 6.4 % with respect to the corresponding base case, whereas a vacuum drying time equal to 4 hours generated an average reduction of the emissions equal to 18.3 %.

On the basis of the performed scenario analysis, an improved solution was proposed (De Marco et al., 2017), considering a freezing time equal to 12 hours and a vacuum drying time equal to 4 hours. In Table 5, the emissions obtained in the improved scenario at midpoint level and their comparison with the base case, were reported.

Table 5: ReCiPe midpoint results in the improved scenario (FT = 12 hours and VT = 4 hours) and their comparison with the base case. Data are referred to the FU.

Midpoint category	Unit	Emissions for improved scenario	Emissions reduction
CC	kg CO_2 eq	3.15E-01	-13%
OD	kg CFC-11 eq[1]	8.85E-09	-23%
TA	kg SO_2 eq	9.03E-04	-17%
FE	kg P eq	3.19E-05	-28%
ME	kg N eq	1.95E-03	-27%
HT	kg 1,4DCB eq[1]	2.56E-02	-26%
POF	kg NMVOC[1]	6.57E-04	-12%
PMF	kg PM_{10} eq	2.75E-04	-17%
TET	kg 1,4DCB eq[1]	1.10E-05	-26%
FET	kg 1,4DCB eq[1]	1.24E-03	-25%
MET	kg 1,4DCB eq[1]	1.18E-03	-25%
IR	kBq U235 eq[1]	3.59E-02	-28%
ALO	m^2 x yr	5.43E-03	-28%
ULO	m^2 x yr	7.68E-04	-28%
NLT	m^2	2.65E-05	-28%
WD	m^3	1.62E-04	-47%
MRD	kg Fe eq	1.96E-03	-26%
FD	kg oil eq	4.69E-02	-22%

[1] CFC-11: Chlorofluorocarbon; 1,4DCB: 1,4 dichlorobenzene; NMVOC: Non Methane Volatile Organic Carbon compound; U235: Uranium 235.

In the end, the normalised emissions related to the base cases (freeze drying and osmotic dehydration + freeze drying) and the improved osmotic dehydration + freeze dying scenario at the endpoint level; i.e., in terms of damages to human health, ecosystem diversity and resource availability, were evaluated and reported in Figure 5. In Figure 5, all the stages of the processes (from agricultural to end of life) were considered.

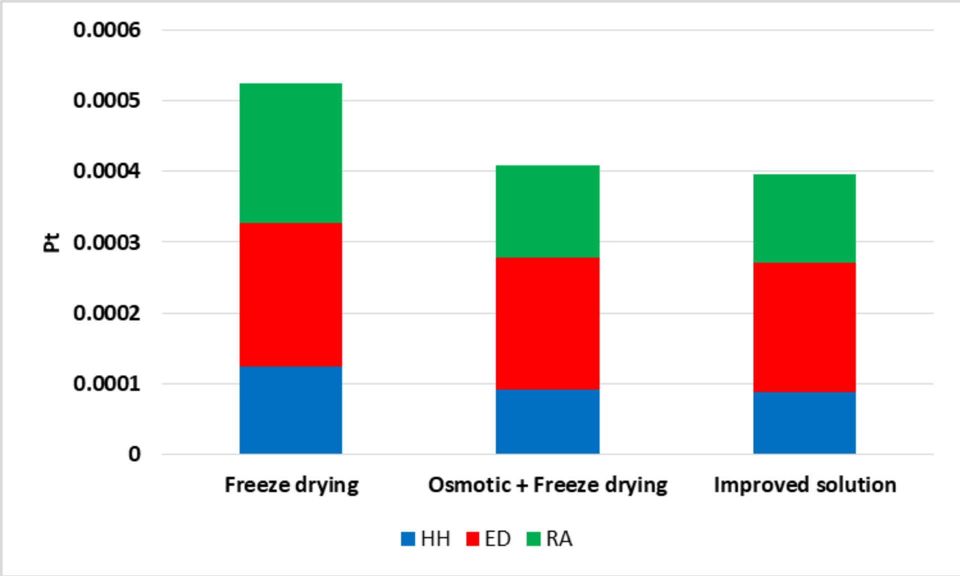


Figure 5. Total environmental impact according to the damage categories of ReCiPe method on relative scale (point, Pt).

The improved solution generated a reduction equal to 4.6 % in terms of HH, 1.2 % in terms of ED and 5.6 % in terms of RA with respect to the corresponding base case (osmotic + freeze drying). Moreover, it is possible to compare the improved solution to the freeze drying scenario (which is the one commercially used), noticing a reduction equal to 29.2 % in terms of HH, 9.4 % in terms of ED and 37.1 % in terms of RA.

4.3 Sensitivity analysis

In a sensitivity analysis, the impact of some of the input parameters on the results has to be investigated. In particular, considering the improved solution, the sensitivity of the results to changes in the following parameters was tested:

a) different fertilisation strategies; i.e., the amount of fertiliser was varied in the range ± 20 %;

b) different transport distance, assuming that strawberries were cultivated at a longer transportation distance;

c) variation of ± 20 % of condenser and vacuum pump power.

The results showed that a modification in the "fertilisation strategies" has an almost imperceptible influence, causing variations of 3 % on human health, less than 1 % on ecosystem diversity and 4 % on resource availability. Indeed, although the quantity of fertiliser varies between -20 % and +20 %, emissions due to agricultural stages ranged between -7 % and +7 %.

In this study, it was assumed that the average transport distance of cultivated strawberries to facility is 250 km. A distance of 500 km would result in a variation of 15 % on human health, of 3 % on ecosystem diversity and 20 % on resource availability. This result can be explained considering the contribution of the transport distance on ozone depletion.

The packaged strawberries were unaffected by the change in condenser and vacuum pump power as none of the endpoint impact categories varied of more than 2 %.

5. **From the sensitivity analysis it can be concluded that variations in fertilisers' amount and in condenser and vacuum pump power did not cause significant changes to the results, whereas variations in transport distances can cause moderate changes in the results. Conclusions**

In this work, a comparative LCA analysis on traditional freeze drying and the combination of osmotic dehydration + freeze drying was performed, considering a "from cradle to grave" approach. Primary data on the different productions were used to compile the life cycle inventory, through mass and heat balances.

Quantitative evaluations showed that agricultural steps, packaging and end of life only marginally influence emissions, whereas processing steps are the main contributors. Therefore, a scenario analysis was performed, considering only the processing steps and varying two characteristic times of the process: the freezing time and the vacuum drying time. This analysis revealed that the process is sensitive to vacuum drying time and rather insensitive to freezing time; indeed, a reduction of the freezing time from 18 to 12 hours generated a lowering of the emissions of 6.4 % and the reduction of the vacuum drying time from 7 to 4 hours generates a lowering of the emissions of about 18.3 %, considering only the processing steps. An improved solution was, therefore, proposed and emissions at endpoint level (considering all the stages of the process) were determined to quantitatively compare the improved solution to the two base cases. The improved scenario generated a global reduction of the emissions of 4 % with respect to the osmotic + freeze drying treatment and of 25 % with respect to the commercially used freeze drying. The improved solution, consisting in the use of the osmotic pre-treatment with reduced process times, could have an important impact on the sustainability of the freeze drying process both from the economic and environmental point of view. Indeed, considering that drying is frequently used in food industries, a reduction of the impact equal to 29.2 % on human health, 9.4 % on ecosystem diversity and 37.1 % on resource availability would lead to cleaner productions in food industries using drying operations. A sensitivity analysis revealed that the results are moderately sensitive to transport distances.

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